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**INSTITUTE OF GAS TECHNOLOGY  
TECHNOLOGY CENTER  
CHICAGO 16, ILLINOIS**

**STUDY OF THE FUNDAMENTALS OF COMBUSTION**

**REPORT NO. 7**

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**FOR**

**OFFICE OF NAVAL RESEARCH**

**DEPARTMENT OF THE NAVY**

**WASHINGTON, D. C.**

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### ABSTRACT

This report presents the results of a study of the burning velocities of the methane-oxygen-nitrogen system at a constant theoretical adiabatic flame temperature of  $2000^{\circ}\text{K}$  at one atmosphere pressure.

The data were obtained on flow nozzle burners with the gas flow to the burner adjusted to produce a flat flame above the nozzle opening. The velocity of the unburned gas through the nozzle is then the burning velocity of the gas mixture.

The burning velocities found by this method are higher than those reported with the tube burner. The increase in burning velocity appears to be due chiefly to a decrease in the quenching effect of the surrounding air. This quenching tends to lower the flame temperature. The ease of formation of polyhedral flames increased as the oxygen to methane ratio increased, indicating the possibility of the existence of methane rich zones that give temperatures higher than the calculated  $2000^{\circ}\text{K}$ . This would also increase the burning velocity.

The composition of a series of methane-oxygen-nitrogen mixtures having theoretical adiabatic flame temperatures of  $2250^{\circ}\text{K}$  at one atmosphere pressure are reported. Included also are the composition of several methane-oxygen-argon mixtures having a theoretical adiabatic flame temperature of  $2000^{\circ}\text{K}$  at one atmosphere.



## INTRODUCTION

This report presents the results of the work performed during the period July 1, 1952 to December 31, 1952 on "A Study of the Fundamentals of Combustion," jointly sponsored by the Office of Naval Research, Science Division, Power Branch and by the Institute of Gas Technology in the laboratories of the Institute of Gas Technology at Chicago, Illinois.

The burning velocities of the methane-oxygen-nitrogen system were investigated for six mixtures having constant theoretical adiabatic flame temperatures of 2000°K and oxygen to methane ratios ranging from 0.78:1.0 to 5.0:1.0. These data were obtained on flow nozzle burners of one-half, three-fourths and one inch diameters. The results were compared with the previous data reported using a three-eighths inch diameter tube burner.

The effects of combustion in air and in an atmosphere of combustion products were studied.

Calculations were made for a series of methane-oxygen-nitrogen mixtures having theoretical adiabatic flame temperatures of 2250°K at one atmosphere pressure. Included also are the composition of several methane-oxygen-argon mixtures having a theoretical flame temperature of 2000°K.

### EXPERIMENTAL PROCEDURE

The calculated mixtures of gases\* used in these determinations were metered separately through critical flow orifices which were calibrated before and after each individual determination. The metered gases were then sent through a mixing "T" to the flow nozzle burner. A side-stream of the gases flowing to the burner was withdrawn through a rotameter (calibrated on the gas mixture flowing to the burner) at such a rate that the gas flow through the nozzle produced a flat flame just above the nozzle opening. The volumetric flow to the nozzle divided by the nozzle area then gave the burning velocity of the gas mixture. The following equation was used for this calculation:

$$V_B = (Q_T - Q_S) / \pi R^2$$

where  $Q_T$  = total metered gas flow (CF/sec.)

$Q_S$  = side-stream gas flow (CF/sec.)

$R$  = radius of nozzle burner (ft.)

$V_B$  = burning velocity (ft./sec.)

The burning velocity was also checked by the cone height method using a three eighths inch burner, as described in Report No. 6, and using the same gas mixtures.

The effect upon the burning velocity of the atmosphere in which the combustion takes place was examined by determining the burning velocity in the open atmosphere and then determining it with the flow nozzle shielded with a tight fitting glass mantle three inches in diameter and eighteen inches high.

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\*See Table I for analyses of gases used.

**TABLE I**  
**ANALYSES OF GASES BY MASS SPECTROMETER**

<u>Methane</u> <u>Mole %</u>		<u>Oxygen</u> <u>Mole %</u>		<u>Nitrogen</u> <u>Mole %</u>	
CH <sub>4</sub>	99.5	O <sub>2</sub>	99.1	N <sub>2</sub>	99.9
C <sub>2</sub> H <sub>6</sub>	0.2	N <sub>2</sub>	0.9	A	0.1
N <sub>2</sub>	0.3				
CO <sub>2</sub>	trace				

## RESULTS

The results of the burning velocity determinations on the methane-oxygen-nitrogen system at 2000°K and one atmosphere pressure using the flow nozzle method are listed in Table II and presented graphically in Fig. 1. The compositions of the gases fed to the flow nozzle for these determinations are listed in Table III.

Theoretical equilibrium composition of the burned products for the methane-oxygen-nitrogen system at 2000°K and one atmosphere partial pressure are given in Report No. 6.

In examining Fig. 1 it can be seen that the burning velocity curve determined by the flow nozzle method indicates faster burning velocities than those secured by the cone height method. The two burning velocity curves show a close correlation up to an oxygen to methane ratio of 60% of the stoichiometric at which a minimum is indicated by both methods. Beyond the minimum point the burning velocities indicated by the flow nozzle method increase much more rapidly than the velocities indicated by the cone height method.

It has been noted that to the right of the minimum burning velocity point (60% of stoichiometric) the flame secured by the flow nozzle has a great tendency to form a polyhedral flame and once a polyhedral flame is formed the flat topped flame used for the burning velocity determinations is not readily obtainable. This tendency toward polyhedral flame formation increases as the oxygen to methane ratio increases, thus increasing the difficulty in obtaining a flat flame at high oxygen to methane ratios.

The formation of the polyhedral flame indicates a diffusion process taking place which creates methane rich zones in the flame. It is conceivable that these methane rich zones, having a temperature

which is higher than the calculated 2000°K, increase the burning velocity of the flame front yielding a higher indicated burning velocity.

The effect of the difference in aeration in the two methods can also account for the differences in the indicated burning velocities. The geometry of the conical flame is such that there is a much greater possibility for the entrainment of secondary air into the flame zone than with the flat flame obtained with the flow nozzle. This entrained air should have a definite quenching effect, lowering the flame temperature and hence lowering the indicated burning velocity.

To examine this effect of secondary aeration upon the flat flame, a glass mantle three inches in diameter and eighteen inches high was placed around the flame to exclude air and produce an atmosphere of combustion products about the flame. It was found in all cases, both for mixtures above and below the stoichiometric oxygen to methane ratio, that the indicated flame velocity increased. This indicates that below stoichiometric oxygen mixtures, the quenching effect of the included air offsets any increase in the heat released by the combustion due to the excess methane burning with the included oxygen. In placing the mantle about the flame the gases entrained by the flame were heated to a temperature above room temperature and hence the quenching effect would be lessened and the indicated burning velocity would be increased.

The heating effect of the nozzle could also cause the burning velocity curve of the flow nozzle determinations to be above the curve of the cone height determinations. Since the nozzles were uncooled, their temperatures were somewhat above room temperature during the

determinations. This alone could cause a shift upward in the burning velocity curve.

#### Flame Temperature Calculations

The burner inlet gas composition for the methane-oxygen-nitrogen system at 2250°K and one atmosphere pressure with the oxygen to methane ratio and nitrogen to methane ratio are given in Table IV and graphically presented in Fig. 2. The equilibrium compositions of the products of combustion for this system are given in Table V.

Data for the methane-oxygen-argon system at 2000°K and one atmosphere pressure are given in Tables VI and VII and Fig. 3.

It is possible to estimate the composition of any gas mixture that will give a constant theoretical adiabatic flame temperature if the stoichiometric point, the methane rich and oxygen rich point are calculated and plotted as in Figs. 2 and 3. The intermediate points lie on approximately straight lines.

### CONCLUSIONS

- (1) The burning velocities of the methane-oxygen-nitrogen system at 2000°K and one atmosphere pressure, as determined by the flow nozzle method are higher than the velocities as determined by the cone height method.

### RECOMMENDATIONS

- (1) The burning velocity curve for the methane-oxygen-nitrogen system at 2000°K and one atmosphere pressure should be completed over the entire range using the nozzle burners.
- (2) Using controlled cooling of the burner nozzle, the effect of nozzle temperature on burning velocity should be determined.
- (3) Using controlled gas approach temperatures, the effect of the gas approach temperature should be determined.
- (4) The burning velocity curve for the methane-oxygen-nitrogen system at 2250°K and one atmosphere should be run to determine the quantitative effect of flame temperature on the burning velocity of this system.
- (5) The burning velocity curves for the methane-oxygen-argon and methane-oxygen-helium systems should be determined at a 2000°K theoretical flame temperature. The results would indicate whether the drop in burning velocity in the region above the oxygen to methane ratio of 8.0:1.0 is caused by the decrease or absence of nitric oxide. It will be noted that in this region the fraction of methane is constant and oxygen is substituted for nitrogen until an oxygen to methane ratio of 11.41:1.0 is reached at which point there is no nitrogen in the mixture.

The effect on burning velocity of the thermal conductivity of the diluent gas would be shown with the use of argon and helium as the third component.



**ACKNOWLEDGEMENT**

The authors gratefully acknowledge the assistance of E. Anderson in the collection and calculation of the data.

**TABLE II**  
**EXPERIMENTAL DATA OBTAINED ON A NOZZLE BURNER**  
**FOR THE BURNING VELOCITY FOR THE**  
**METHANE-OXYGEN-NITROGEN SYSTEM**  
**AT 2000°K AND ONE ATMOSPHERE PRESSURE**

<u>Mole Ratio Oxygen to Methane</u>	<u>Nozzle Diameter (inches)</u>	<u>Volumetric Flow (ft<sup>3</sup>/hr.)</u>	<u>Burning Velocity (ft/sec.)</u>
0.783	0.50	4.45	0.907
0.783	0.50	4.40	0.896
1.20	1.00	11.31	0.576
1.20	1.00	10.99	0.560
1.60	1.00	20.21	1.029
1.60	1.00	20.11	1.024
2.00	1.00	15.19	0.773
2.00	1.00	18.04	0.919
3.00	1.00	30.55	1.556
3.00	0.75	17.85	1.616
5.00	0.50	9.156	1.865

**TABLE III**  
**BURNER INLET GAS COMPOSITION FOR THE**  
**METHANE-OXYGEN-NITROGEN SYSTEM AT 2000°K**  
**AND ONE ATMOSPHERE PRESSURE**

<u>Mole Ratio</u> <u>Oxygen to</u> <u>Methane</u>	<u>Mole Ratio</u> <u>Nitrogen to</u> <u>Methane</u>	<u>Mole</u> <u>Percent</u> <u>Methane</u>	<u>Mole</u> <u>Percent</u> <u>Oxygen</u>	<u>Mole</u> <u>Percent</u> <u>Nitrogen</u>
0.783	0.00	56.07	43.93	0.00
1.20	3.36	17.98	21.58	60.44
1.60	6.67	10.79	17.26	71.95
2.00	9.79	7.82	15.63	76.55
3.00	8.80	7.81	23.43	68.76
5.00	6.63	7.91	39.59	52.49
7.00	4.51	7.99	56.97	36.04
8.00	3.36	8.09	64.70	27.21
9.00	2.44	8.04	72.32	19.64
10.50	0.93	8.05	84.50	7.45
11.41	0.00	8.05	91.95	0.00

**TABLE IV**  
**BURNER INLET GAS COMPOSITION FOR THE**  
**METHANE-OXYGEN-NITROGEN SYSTEM AT ADIABATIC**  
**FLAME TEMPERATURE OF 2250°K AND**  
**ONE ATMOSPHERE PRESSURE**

Datum Temperature: 300°K

<u>Mole Ratio</u> <u>Oxygen to</u> <u>Methane</u>	<u>Mole Ratio</u> <u>Nitrogen to</u> <u>Methane</u>	<u>Mole</u> <u>Percent</u> <u>Methane</u>	<u>Mole</u> <u>Percent</u> <u>Oxygen</u>	<u>Mole</u> <u>Percent</u> <u>Nitrogen</u>
0.856	0.00	55.87	46.13	0.00
2.00	7.28	9.72	19.45	70.83
5.00	4.312	9.70	48.49	41.81
6.00	3.245	9.76	58.57	31.67
7.00	2.193	9.81	68.67	21.52
9.20	0.00	9.81	90.19	0.00

TABLE V  
EQUILIBRIUM COMPOSITION OF THE PRODUCTS FOR THE  
METHANE-OXYGEN-NITROGEN SYSTEM AT A THEORETICAL  
ADIABATIC FLAME TEMPERATURE OF 2250°K  
AND ONE ATMOSPHERE PRESSURE

Datum Temperature: 300°K

<u>Products</u>	<u>Oxygen to Methane Ratio</u>					
	<u>0.856</u>	<u>2.00</u>	<u>5.00</u>	<u>6.00</u>	<u>7.00</u>	<u>9.20</u>
CO <sub>2</sub>	0.025241	0.086077	0.094954	0.095870	0.096443	0.096539
CO	0.307214	0.010333	0.001562	0.001357	0.001216	0.001008
H <sub>2</sub> O	0.211286	0.187259	0.188754	0.189408	0.190061	0.190048
N <sub>2</sub>	0.000000	0.701279	0.410294	0.309025	0.208285	0.000000
O <sub>2</sub>	0.000000	0.005289	0.281610	0.380187	0.479894	0.699148
H <sub>2</sub>	0.450981	0.003942	0.000544	0.000471	0.000420	0.000348
O	0.000000	0.000291	0.002126	0.002470	0.002775	0.003350
H	0.004977	0.000465	0.000173	0.000161	0.000152	0.000138
OH	0.000300	0.002842	0.007701	0.008331	0.008839	0.009704
NO	0.000000	0.002217	0.012376	0.012479	0.011511	0.000000

TABLE VI  
BURNER INLET GAS COMPOSITION FOR THE  
METHANE-OXYGEN-ARGON SYSTEM AT ADIABATIC  
FLAME TEMPERATURE OF 2000°K AND  
ONE ATMOSPHERE PRESSURE

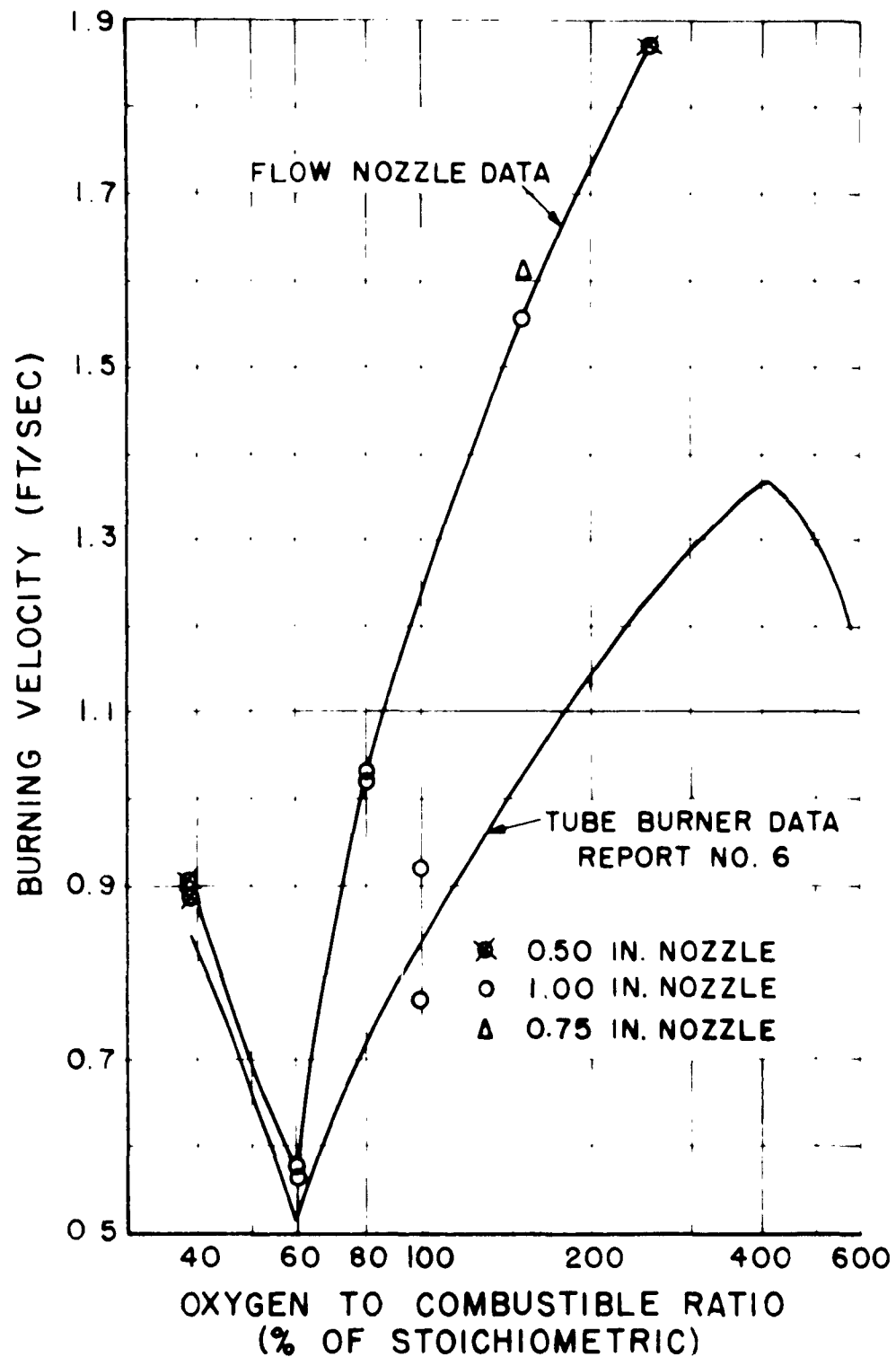
Datum Temperature: 300°K

<u>Mole Ratio</u> <u>Oxygen to</u> <u>Methane</u>	<u>Mole Ratio</u> <u>Argon to</u> <u>Methane</u>	<u>Mole</u> <u>Percent</u> <u>Methane</u>	<u>Mole</u> <u>Percent</u> <u>Oxygen</u>	<u>Mole</u> <u>Percent</u> <u>Argon</u>
0.783	0.0	56.07	43.93	0.0
2.0	15.534	5.40	10.79	83.81
8.0	5.713	6.80	54.37	38.83
11.41	0.0	8.05	91.95	0.0

**TABLE VII**  
**EQUILIBRIUM COMPOSITION OF THE PRODUCTS FOR THE**  
**METHANE-OXYGEN-ARGON SYSTEM AT A THEORETICAL**  
**ADIABATIC FLAME TEMPERATURE OF 2000°K**  
**AND ONE ATMOSPHERE PRESSURE**

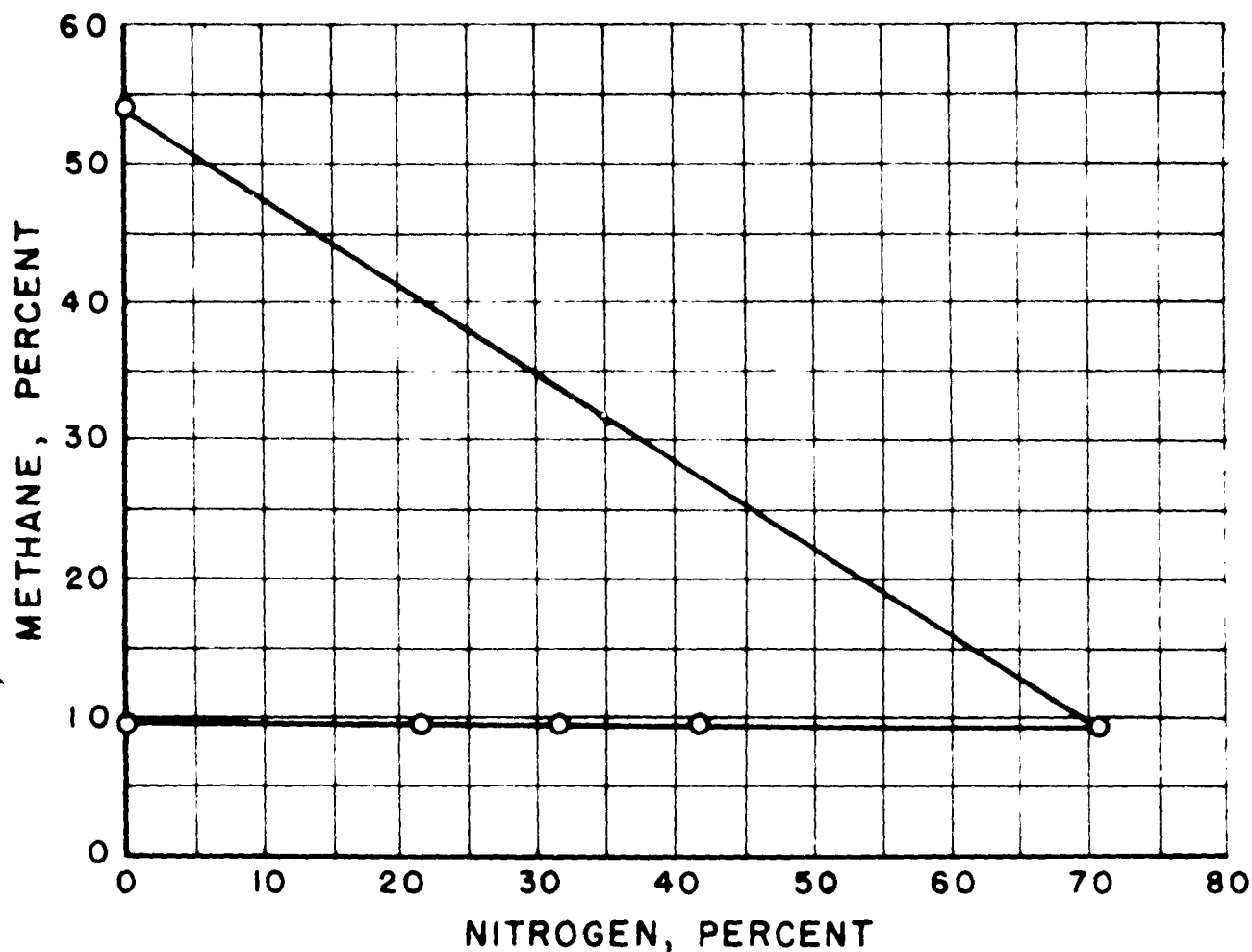
Datum Temperature: 300°K

<u>Products</u>	<u>Oxygen to Methane Ratio</u>			
	<u>0.783</u>	<u>2.00</u>	<u>8.00</u>	<u>11.41</u>
CO <sub>2</sub>	0.021811	0.051909	0.067773	0.080325
CO	0.311311	0.001966	0.000145	0.000126
H <sub>2</sub> O	0.167000	0.106584	0.134532	0.159350
A	0.000000	0.836814	0.387924	0.000000
O <sub>2</sub>	0.000000	0.001307	0.406735	0.756500
H <sub>2</sub>	0.498656	0.000844	0.000060	0.000052
O	0.000000	0.000026	0.000468	0.000638
H	0.001146	0.000047	0.000013	0.000011
OH	0.000032	0.000501	0.002365	0.003005

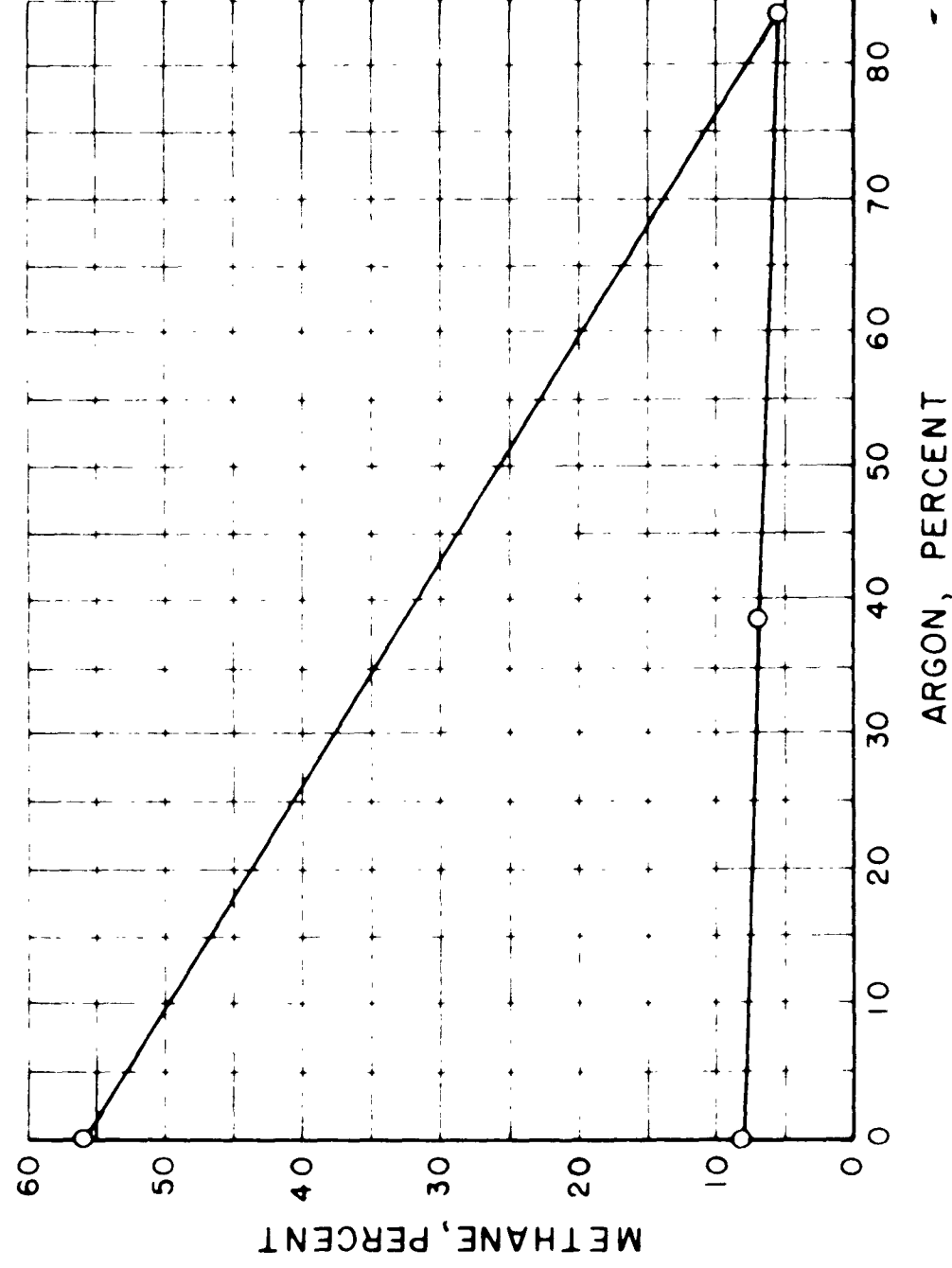


BURNING VELOCITIES OF THE  
 $\text{CH}_4 - \text{O}_2 - \text{N}_2$  SYSTEM AT  $2000^\circ\text{K}$   
AND 1 ATM





UNBURNT GAS COMPOSITION FOR  
THE  $\text{CH}_4\text{-O}_2\text{-N}_2$  SYSTEM AT  
 $2250^\circ\text{K}$  AND ONE ATMOSPHERE PRESSURE



UNBURNT GAS COMPOSITION FOR THE  
CH<sub>4</sub>-O<sub>2</sub> - A SYSTEM AT 2000°K AND  
ONE ATMOSPHERE PRESSURE